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Abstract

A newly-developed soft elastomeric capacitor (SEC) strain sensor has shown promise in fatigue crack monitoring. The SECs exhibit high levels of ductility and hence do not break under excessive strain when the substrate cracks due to slippage or de-bonding between the sensor and epoxy. The actual strain experienced by a SEC depends on the amount of slippage, which is difficult to simulate numerically, making it challenging to accurately predict the response of a SEC near a crack. In this paper, a two-step approach is proposed to simulate the capacitance response of a SEC. First, a finite element (FE) model of a steel compact tension specimen was analyzed under cyclic loading while the cracking process was simulated based on an element removal technique. Second, a rectangular boundary was defined near the crack region. The SEC outside the boundary was assumed to have perfect bond with the specimen, while that inside the boundary was assumed to deform freely due to slippage. A second FE model was then established to simulate the response of the SEC within the boundary subject to displacements at the boundary from the first FE model. The total simulated capacitance was computed from the model results by combining the computed capacitance inside and outside the boundary. The performance of the simulation incorporating slippage was evaluated by comparing the model results with the experimental data from the test performed on a compact tension specimen. The FE model considering slippage showed results that matched the experimental findings more closely than the FE model that did not consider slippage.

Keywords

Fatigue crack, crack detection, capacitive sensor, structural health monitoring, compact tension specimen, slippage, de-bonding; finite element model

Disciplines

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Model Calibration for a Soft Elastomeric Capacitor Sensor Considering Slippage under Fatigue Cracks

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ABSTRACT

A newly-developed soft elastomeric capacitor (SEC) strain sensor has shown promise in fatigue crack monitoring. The SECs exhibit high levels of ductility and hence do not break under excessive strain when the substrate cracks due to slippage or de-bonding between the sensor and epoxy. The actual strain experienced by a SEC depends on the amount of slippage, which is difficult to simulate numerically, making it challenging to accurately predict the response of a SEC near a crack. In this paper, a two-step approach is proposed to simulate the capacitance response of a SEC. First, a finite element (FE) model of a steel compact tension specimen was analyzed under cyclic loading while the cracking process was simulated based on an element removal technique. Second, a rectangular boundary was defined near the crack region. The SEC outside the boundary was assumed to have perfect bond with the specimen, while that inside the boundary was assumed to deform freely due to slippage. A second FE model was then established to simulate the response of the SEC within the boundary subject to displacements at the boundary from the first FE model. The total simulated capacitance was computed from the model results by combining the computed capacitance inside and outside the boundary. The performance of the simulation incorporating slippage was evaluated by comparing the model results with the experimental data from the test performed on a compact tension specimen. The FE model considering slippage showed results that matched the experimental findings more closely than the FE model that did not consider slippage.

Keywords: Fatigue crack; crack detection; capacitive sensor; structural health monitoring; compact tension specimen; slippage; de-bonding; finite element model.

1. INTRODUCTION

Fatigue cracks occurring in steel bridges are of significant concern for structural engineers and bridge owners. Field studies have indicated that fatigue cracks can cause localized failures in structural components and further weaken structural integrity [1]. For most fatigue cracks in steel bridges, the final fracture phase occurs over a relatively short number of cycles, while the majority of the total fatigue life consists of initiation and the subcritical crack propagation phase [2]. This characteristic of fatigue crack propagation, i.e., slow-growth in the subcritical crack propagation phase and rapid-development in the unstable fracture phase, means that detecting cracking during the subcritical phase is of utmost importance so that remedial action can be taken.

Over the past few decades, many techniques have been developed for fatigue crack monitoring [3]. Piezoelectric sensors are a well-established crack detecting technique, and have been implemented in various engineering applications. Grondel [4] applied piezoelectric transducers in riveted aluminum joints and demonstrated the ability to detect fatigue crack activities in that application. Ihn [5, 6] detected the crack growth in an aircraft structure using a diagnostic signal generated by built-in piezoelectric actuators. However, piezoelectric transducers require an additional source to generate

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the signal, which may increase the complexity of the system design. Acoustic emission sensors have also been tested in the field to detect crack activities in steel bridges [7]. Strain-based sensing approaches represent another structural health monitoring technique which can be used to detect cracks in structures. Fiber optic strain sensors are one of these techniques and have been well investigated to monitor localized deformations of structural components in civil infrastructure. Mohamad [8] used a distributed fiber optic strain-sensing method and successfully estimated axial and lateral movements of a secant-piled wall. Yasue [9] and Tapanes [10] developed the fiber optic sensor to monitor cracks in concrete pipes. Nevertheless, fiber optic sensors are not commonly applied in monitoring fatigue cracks of steel bridges, partly because of the difficulty of embedding them in steel structures [11]. Furthermore, while fiber optic strain sensors can identify the location of cracks, they are prone to damage and may fail to monitor crack propagation continuously due to the brittle nature of the sensing material. Inspired by large area electronics, Yao and Glisic [12] applied a thin-film sensing sheet with an array of strain sensors to detect fatigue cracks in steel components. Test results showed the sensing sheet could successfully capture crack growth. However, the sensing sheet's measurement may become sensitive to crack positions and orientations [13].

Recently a large-size, flexible capacitive strain sensor has shown potential in crack monitoring. Compared with traditional foil strain gauges, this newly-developed soft elastomeric capacitor (SEC) sensor is soft and extremely ductile, leading to a maximum 20% measurement range of strain [14]. With a varying sensing area, the SEC sensor is able to detect crack propagation over a large surface area. A number of studies [15-17] indicated that the SEC sensor could accurately measure strain variation of the detected surface by measuring the capacitance change. To investigate the SEC sensor's performance on fatigue crack monitoring, several fatigue tests have been conducted with compact tension C(T) specimens [18, 19]. Test results have shown that the SEC sensor successfully detected crack growth induced by fatigue loading under a constant load range. To better understand the behavior of the SEC sensor in the presence of fatigue cracks, the authors applied a Finite Element (FE) method to simulate the SEC sensor's response to a fatigue crack [20]. An algorithm was also created such that numerical results of the FE model could be directly converted to the SEC's capacitance response assuming perfect bond between the SEC sensor and specimen. A comparison between simulation and test results showed that the FE model overestimated the sensor's response, especially when crack size was large. This might be due to slippage or de-bonding between the sensing skin and epoxy. Such behaviors may become significant when crack sizes are large, making it difficult to simulate the response of the SEC under fatigue cracks numerically.

In this paper, a revised method is proposed to simulate slippage and de-bonding behavior of the sensing skin in a FE model. To evaluate the effectiveness of this method, a fatigue test was performed with a C(T) specimen, in which the crack growth was measured continuously using a crack opening displacement (COD) gage. Section 2 briefly introduces the sensing principles of the SEC sensor. The issue of slippage and de-bonding between the sensor and specimen under crack growth is also discussed. A new fatigue test performed with the SEC sensor was used to calibrate the FE model, and this is introduced in Section 3. The new modeling approach which simulates slippage and de-bonding behaviors of the SEC sensor is presented in Section 4. The performance of this approach was evaluated through the comparison between the calibrated simulation and test results.

2. SOFT ELASTOMERIC CAPACITOR SENSOR

2.1 Sensing principle

A schematic of the SEC sensor is shown in Fig. 1. The sensor is fabricated with a soft polymer material with stretchable electrodes to create a highly flexible and stretchable capacitor with three layers. The middle dielectric layer is fabricated with poly-styrene-co-ethylene-co-butylene-co-styrene (SEBS) doped with titanium dioxide, while the top and bottom layers are stretchable electrodes composed of SEBS mixed with carbon black. To measure the capacitance of the sensor, two conductive copper tabs are attached on both top and bottom layers. Detailed descriptions and fabrication process of the SEC sensor can be found in [14] and [15]. Fig. 2 shows a picture of the SEC sensor.

The SEC sensor measures strain of the detected structure by converting the sensor's geometric change (area and thickness) under strain into capacitance change. Eq. 1 shows such a relationship, in which C is the capacitance of the SEC sensor, ϵ_0 is the permittivity of the vacuum, ϵ_r is the dimensionless relative permittivity, A is the sensing area, and h is the thickness of the sensor.

$$C = \frac{e_0 e_r A}{h} \quad (1)$$

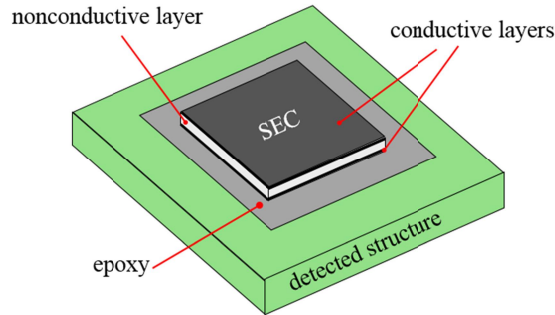


Figure 1. Schematic of the SEC sensor

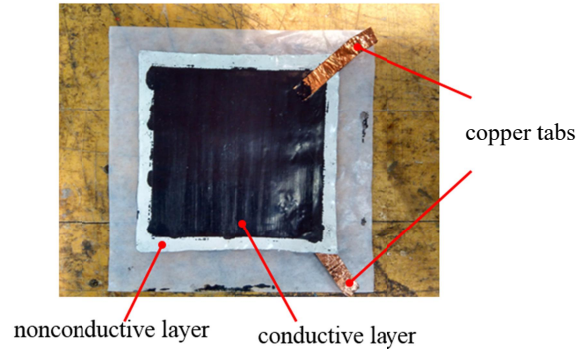


Figure 2. Picture of the SEC sensor

For the case of unidirectional strain, the relationship between the capacitance change ratio and strain can be established as in Eq. 2 [14], where C is the initial capacitance of the sensor, ΔC is the capacitance change, and ε is the unidirectional strain that the SEC sensor experiences.

$$\frac{\Delta C}{C} = 2\varepsilon \quad (2)$$

In the application of crack monitoring, however, the SEC sensor may be subjected to a biaxial and nonuniform strain field. To address this concern, the authors used Eq. 3 to describe the sensing principle of the SEC sensor under a biaxial strain field [19], where ε_x and ε_y are the strains at two principal axes.

$$\frac{\Delta C}{C} = (1 + \varepsilon_x)^2 (1 + \varepsilon_y)^2 - 1 \quad (3)$$

2.2 Slippage and de-bonding of the SEC sensor under cracking

The sensing skin could experience high levels of strain under the action of fatigue crack growth. In fact, assuming perfect bond between the SEC sensor and substrate, the theoretical strain at the crack is infinite since the crack opening region has zero initial length. As shown in Fig. 3a, when the crack grows into the sensor area, the epoxy layer between the sensor and detected surface (Fig. 3b) will break due to the limited deformation capacity of epoxy. However, as the SEC sensor is made of a highly ductile material, the crack opening does not cause it to break. To resist such a high level of strain, a reasonable assumption is that the sensing skin may de-bond from the epoxy layer within a localized region along the crack path (Fig. 3c).

The de-bonding behavior at the interface between sensing material and bonding agent commonly exists in many strain-based monitoring techniques. Dai et al. [21] reported de-bonding occurred at fiber/matrix interface of a carbon nanotube-based composite sensor, and further mentioned that such a behavior could influence the sensor's measurement. Imai and Feng [22] found an interfacial slippage occurred between the fiber core and its surrounding material in a study of crack monitoring using optical fiber sensors. The sensor's measurement may underestimate the crack size due to the slippage. A similar slippage phenomenon in the application of optical sensors was also confirmed in Wu and Zhang's experimental work [23]. These findings indicate that slippage and de-bonding behavior must be considered in the application of these strain sensors since they may affect the accuracy of the sensor measurement.

Due to the fact that the slippage area is limited and occurs beneath the sensing skin (Fig. 3c), observation and quantification of the amount of slippage occurring during experimental tests is difficult. Instead, the size of slippage area can be quantified through numerical calibration of the FE model based on experimental tests. By defining a specific area in the FE model in which the sensing skin is able to deform freely, it becomes feasible to simulate the sensor response over a slippage area. The analytical results are compared with test results to quantify the slippage area. The FE calibration method is described in Section 4.

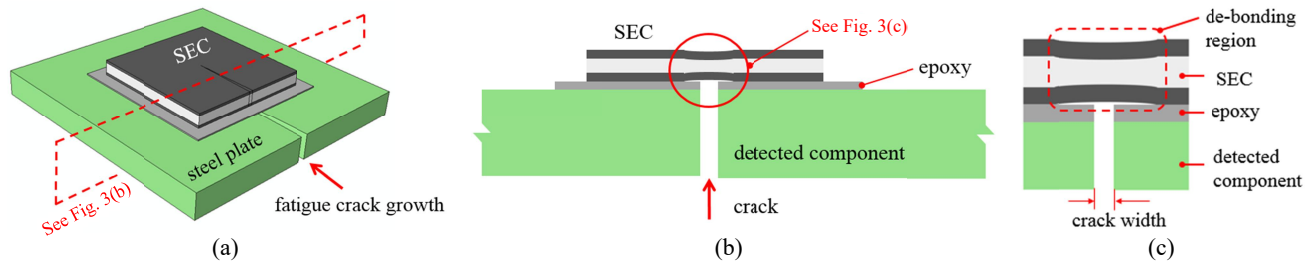


Figure 3. (a) Crack activity monitored by the SEC sensor; (b) de-bonding behavior of the sensing skin; and (c) a detailed schematic at the de-bonding region

3. EXPERIMENTAL TEST

3.1 Test setup

An experimental test was performed on a steel C(T) specimen, and was used to calibrate the numerical model. Several similar tests have been conducted by Kharroub et al. [18], showing that the sensor is able to detect crack growth by measuring an increased capacitance response. However, since crack size was only measured when the change of SEC's signal was observed, the test data are insufficient to establish a quantitative relation between sensor response and crack size. Subsequently, a new test was conducted by the authors [19] with an updated experimental approach. The actuator was paused multiple times to take quality pictures of the specimen when the crack grew an additional 1/16 in. such that the corresponding crack sizes could be measured by counting pixels of the crack in the pictures, enabling quantification of the relationship between the sensor's response and crack size. Nevertheless, the crack size was measured at discrete points and pausing the actuator seemed to add noise to the sensor's reading, which increased the complexity and uncertainty in data processing.

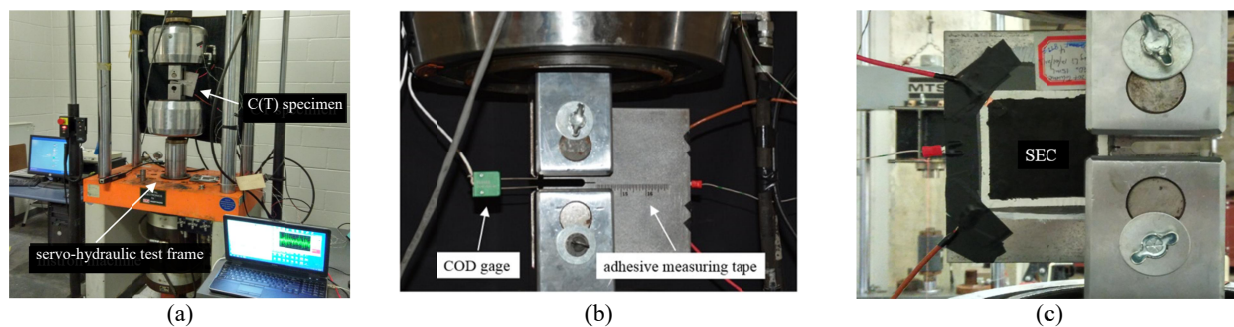


Figure 4. (a) Test setup before installing the C(T) specimen; (b) front view of the specimen; and (c) back view of the specimen

To overcome these limitations in the new test, a crack opening displacement (COD) gage was applied to continuously measure crack growth without pausing the actuator. The C(T) specimen was fabricated from a 1/4 in. thick A36 steel plate. Detailed dimensions of the C(T) specimen can be found in Fig. 5a. Two knife edges were fabricated at the front

face of the C(T) specimen to install the COD gage (epsilon 3541-0030-150T-ST). In addition, an adhesive measuring tape was attached on the surface of the C(T) specimen along the crack path to enable observation of crack growth during the test (Fig. 4b). The SEC sensor was attached on the back side of the C(T) specimen (Fig. 5b) and connected to a data acquisition (DAQ) system (Fig. 4c). An off-the-shelf DAQ board (ACAM PCap02) was adopted to measure the sensor's capacitance response at a sampling rate of 25 Hz. To minimize measurement noise due to electromagnetic interference, the DAQ board was sealed in an aluminum box, as shown in Fig. 5c.

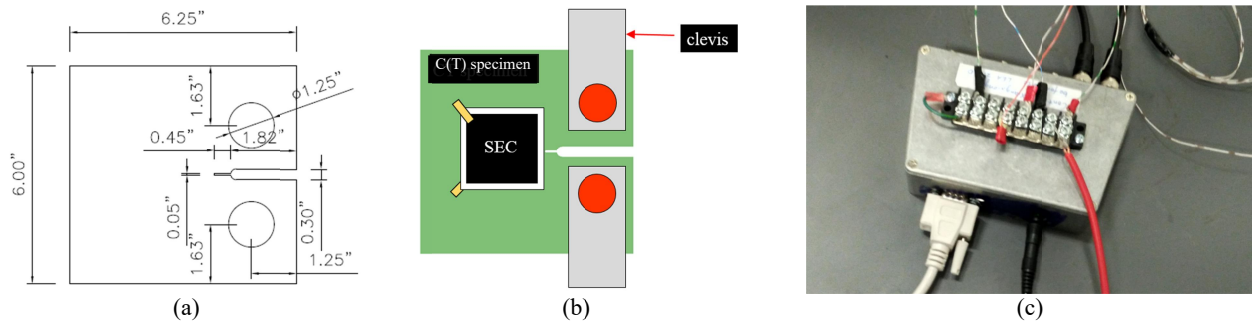


Figure 5. (a) Dimensions of the C(T) specimen; (b) sensor arrangement; and (c) off-the-shelf DAQ housed in an aluminum box

3.2 Preliminary test results

A constant load range from 0.65 kip to 6.5 kip with a 2 Hz loading rate was applied in the test. The crack initially grew to 33/32 in. over 5,832 cycles. The specimen sustained 14,516 cycles until it failed completely. Fig. 6a shows a picture of the specimen taken when the crack length reached approximately 1/4 in.

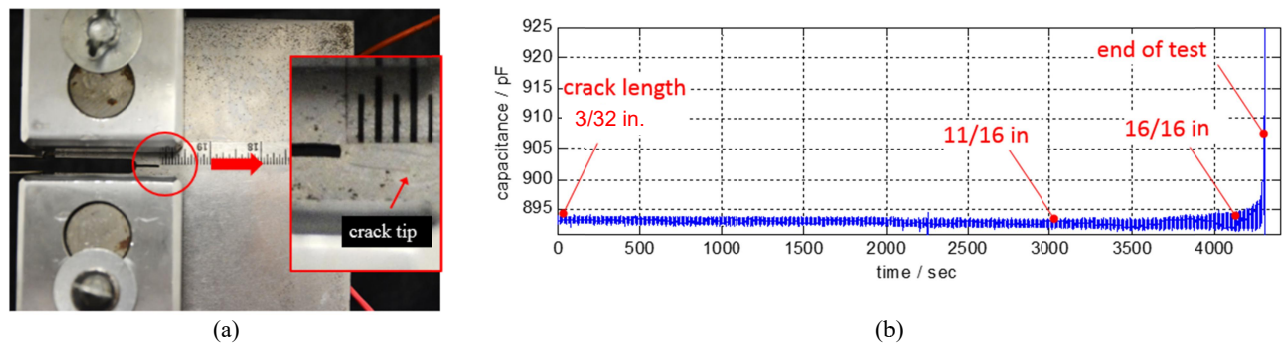


Figure 6. (a) Crack growth on the C(T) specimen; and (b) sensor measurement

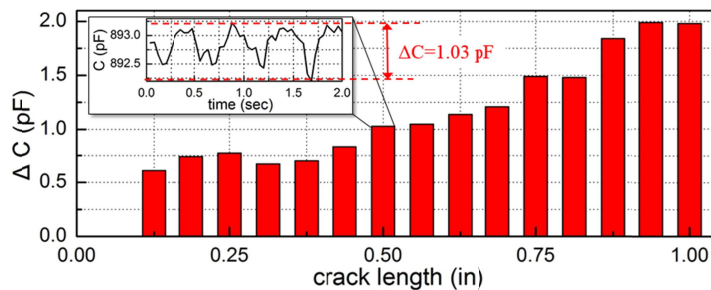


Figure 7. Range of capacitance measurement vs. crack length

The full time history of the raw capacitance measurement taken by the sensor is shown in Fig. 6b. Typical stages of crack growth are also labeled in the plot. Capacitance was measured from when the crack length reached approximately 3/32 in. until the end of the test. The test results indicated that the sensor detected crack growth by showing a significant increase in capacitance when the crack size was large (Fig. 6b). However, sensor response at the early stages of fatigue initiation and growth was less clear. To address this issue, a different approach is proposed here by evaluating the ranges, i.e. the difference between the maximum and minimum capacitance, at the times when the crack length increases by an additional 1/16 in. The relationship is shown in Fig. 7. To eliminate the high noise content from the raw measurement, the data was low-pass filtered with a cut-off frequency of 9 Hz. The results show an increasing trend for ΔC with increasing crack length. It was found that ΔC increased from 0.6 pF to 1 pF when the crack length increased from 1/8 in. to 1/2 in. The change in capacitance, ΔC , reached 2 pF when crack length reached 1 in. These results indicate that crack growth can be detected at the beginning stage of the fatigue crack.

4. FINITE ELEMENT MODEL CALIBRATION

4.1 Finite Element model

To investigate the mechanical behavior of the SEC sensor under crack growth, a FE model was created in Abaqus v.6.13.3. A detailed description of the model can be found in [20]. The FE model was built using shell elements to have the same geometrical dimensions as the physical C(T) specimen (Fig. 8a). A damage evolution theory combined with an element removal technique was used to simulate crack growth in the FE model. As shown in Fig. 8b, when a cyclic load was applied in the model, the highlighted element at the tip of the notch exhibited the highest-magnitude stress due to the stress concentration at the crack tip, making it the first element to accumulate sufficient damage to be removed from the model. Using this technique, damaged elements were removed sequentially from the model according to the damage evolution function, simulating crack propagation under cyclic loading as shown in Fig. 8c.

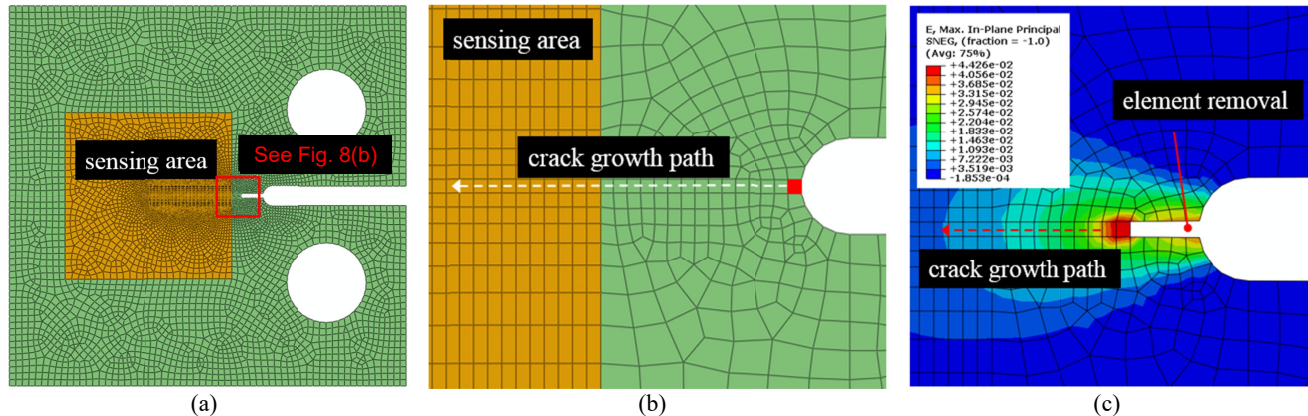


Figure 8. (a) FE model and mesh; (b) a detailed look at the tip of the pre-crack; and (c) strain distribution when crack grows

The SEC sensor was not physically modeled in the FE model, therefore, numerical results from the FE model needed to be converted to the capacitance change of the SEC sensor to allow for a comparison with the experimentally-obtained data. Based on the fact that the sensor was firmly attached to the detected structure, the SEC sensor should experience the same deformation as the structure within the sensing area as highlighted in Fig. 8a and 8b (i.e., strain compatibility). Therefore, the capacitance change experienced in a SEC sensor can be computed based on the change in area of the sensing area under application of loads, as according to Eq. 4 [20]. When applying Eq. 4, $\Delta C/C_0$ is the percentage of capacitance change in the sensing area, A_0 is the initial sensing area, A_{0i} and A_{1i} are the initial and deformed area for each element in the sensing area, and there are 7,102 elements in the sensing area. An assumption was made that the strain

within each element in the sensing area was uniformly distributed due to the small size of the elements, even though the strain distribution over the entire sensing area is highly non-uniform due to the crack.

$$\frac{\Delta C}{C_0} = \frac{1}{A_0} \sum_{i=1}^{7102} A_{0i} \left(\frac{A_{1i}^2}{A_{0i}^2} - 1 \right) \quad (4)$$

4.2 Simulation approach considering slippage

A two-step approach is proposed here to simulate the capacitance response of the SEC sensor considering the effects of slippage. First, the FE model of the specimen was analyzed under cyclic loading while the cracking process was simulated based on the element removal technique described previously (Fig. 8c). Second, a rectangular boundary (Fig. 9) was defined near the crack region. The length of the rectangular boundary was the same as the final crack length in the test. The width was chosen to minimize the discrepancy between the capacitance responses from simulation and the experiment. The sensing area outside this boundary was assumed to have perfect bond with the specimen, while the region inside the boundary was assumed to deform freely due to slippage. A separate FE model was then established to simulate the response of the SEC within the boundary subject to displacements at the boundary (the red dots in Fig. 9) from the first FE model. The total simulated capacitance computed from the model results is obtained by combining the simulated capacitance computations performed for elements inside and outside the boundary.

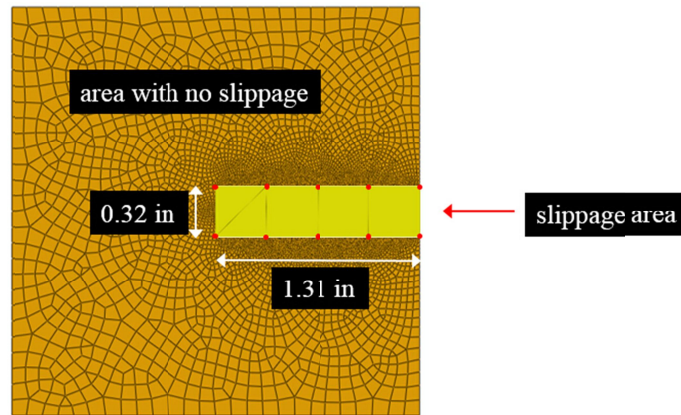


Figure 9. The sensing area considering slippage

4.3 FE model calibration

The slippage simulation method was evaluated by first comparing the FE models with and without considering slippage. Then, these results were compared with the experimental test results described in Section 3. Fig. 10 shows this comparison, where red, black, and blue bars represent experimental data, the FE model without considering slippage, and the FE model considering slippage, respectively. Between the results of two FE models, the model considering slippage showed similar capacitance change of the SEC sensor when crack length was less than 1/2 in. However, the FE model considering slippage showed better agreement with experimental results when the crack size becomes large.

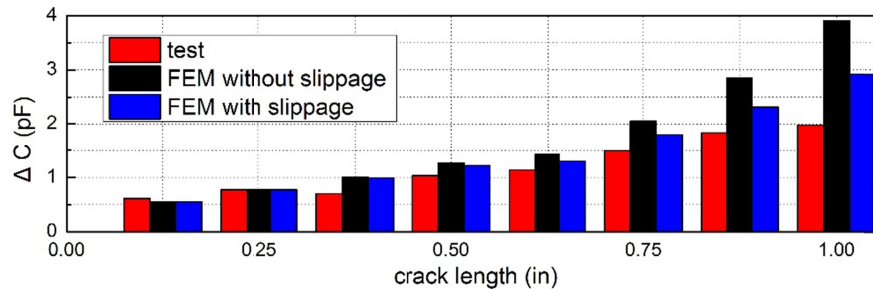


Figure 10. Amplitude of measurement with crack growth

5. CONCLUSIONS

The high ductility and large size of sensing area of the SEC sensor implies great promise in monitoring fatigue cracks. A numerical simulation approach was proposed to study the mechanism of the SEC sensor under the action of fatigue crack growth. The simulated sensor response, however, showed differences with test results due to potential slippage and de-bonding between the SEC sensor and detected structure. To consider the effects of slippage and de-bonding, a revised numerical approach is proposed by creating an area of slippage in the FE model, in which the sensor can deform freely. The performance of this revised approach is evaluated by comparing the results of the FE models with and without slippage and a new experimental result. The comparison indicates that the FE model considering slippage can predict better the sensor's response especially when the crack length is large.

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